

GAUDIN'S MODEL AND THE GENERATING FUNCTION OF THE WRONSKI MAP

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ABSTRACT. We consider the Gaudin model associated to a point $z \in \mathbb{C}^n$ with pairwise distinct coordinates and to the subspace of singular vectors of a given weight in the tensor product of irreducible finite-dimensional sl_2 -representations, [G]. The Bethe equations of this model provide the critical point system of a remarkable rational symmetric function. Any critical orbit determines a common eigenvector of the Gaudin hamiltonians called a Bethe vector.

In [ReV], it was shown that for generic z the Bethe vectors span the space of singular vectors, i.e. that the number of critical orbits is bounded from below by the dimension of the space of singular vectors. The upper bound by the same number is one of the main results of [SV].

In the present paper we get this upper bound in another, “less technical”, way. The crucial observation is that the symmetric function defining the Bethe equations can be interpreted as the generating function of the map sending a pair of complex polynomials into their Wronski determinant: the critical orbits determine the preimage of a given polynomial under this map. Within the framework of the Schubert calculus, the number of critical orbits can be estimated by the intersection number of special Schubert classes. Relations to the sl_2 representation theory ([F]) imply that this number is the dimension of the space of singular vectors.

We prove also that the spectrum of the Gaudin hamiltonians is simple for generic z .

1. INTRODUCTION

The Gaudin model of statistical mechanics is a completely integrable quantum spin chain associated to the Lie algebra $sl_2 = sl_2(\mathbb{C})$, [G]. Denote L_{λ_j} the irreducible sl_2 -module with highest weight $\lambda_j \in \mathbb{C}$. The space of states of the model is the tensor product $L = L_{\lambda_1} \otimes \cdots \otimes L_{\lambda_n}$. Associate with any L_{λ_j} a complex number z_j , and assume z_1, \dots, z_n to be pairwise distinct numbers, $z = (z_1, \dots, z_n)$. The Gaudin hamiltonians $\mathcal{H}_1(z), \dots, \mathcal{H}_n(z)$ are mutually commuting linear operators on L which are defined as follows,

$$\mathcal{H}_j(z) = \sum_{i \neq j} \frac{\Omega_{ij}}{z_j - z_i}, \quad j = 1, \dots, n,$$

where Ω_{ij} is the operator which acts as the Casimir element on i -th and j -th factors of L and as the identity on all others.

One of the main problems in the Gaudin model is to find common eigenvectors and eigenvalues of the Gaudin hamiltonians, and the algebraic Bethe Ansatz is one of the most effective methods for solving this problem. The idea of this method is to find some function with values in the space of states, and to determine a certain special value of its argument in such a way that the value of this function is an eigenvector. The equations which determine these special values of the argument are called *the Bethe equations*, and the common eigenvector corresponding to a solution of the Bethe equations, is called *the Bethe vector*, [FaT].

It is enough to diagonalize the Gaudin hamiltonians in the subspace of singular vectors of a given weight. The Bethe equations associated to the space $\text{Sing}_k(L)$ of singular vectors of the weight $\lambda_1 + \dots + \lambda_n - 2k$, where k is a positive integer, have the form

$$\sum_{l=1}^n \frac{\lambda_l}{t_i - z_l} = \sum_{j \neq i} \frac{2}{t_i - t_j}, \quad i = 1, \dots, k.$$

This system is symmetric with respect to permutations of unknowns t_1, \dots, t_k , and any (orbit of) solution $t^0 = (t_1^0, \dots, t_k^0)$ to this system defines an eigenvector $v(t^0) \in \text{Sing}_k(L)$ of the Gaudin hamiltonians $\{\mathcal{H}_j(z)\}$, [G].

A conjecture related to Bethe Ansatz says that the Bethe vectors give a basis of the space of states. For the sl_2 Gaudin model, the conjecture was proved in [ReV] in the case of generic z and generic (non-resonant) weights $\lambda_1, \dots, \lambda_n$. In the case of *integral dominant* weights, which is a non-generic one, results of Sec. 9 of [ReV] imply only that for generic z the number of Bethe vectors is *at least* the dimension of the space of singular vectors, see also Theorem 8 in [SV]. The proof of the Bethe Ansatz conjecture for the sl_2 Gaudin model was completed in our work with A. Varchenko [SV], where the bound from above for the number of the Bethe vectors by the dimension of the space of singular vectors was obtained.

In [SV], we study the function

$$\Phi(t) = \prod_{i=1}^k \prod_{l=1}^n (t_i - z_l)^{-\lambda_l} \prod_{1 \leq i < j \leq k} (t_i - t_j)^2.$$

If all λ_l are positive integers, then this function is rational, and the Bethe equations are exactly the equations on the critical points of this function with non-zero critical values,

$$\frac{1}{\Phi(t)} \cdot \frac{\partial \Phi}{\partial t_i}(t) = 0 \quad i = 1, \dots, k.$$

The upper bound for the number of critical orbits of the function $\Phi(t)$ with non-zero critical values by the dimension of $\text{Sing}_k(L)$ is one of the main results of the paper. The proof is difficult, see Theorems 9–11 of [SV]. As we point out in Sec. 1.4 of [SV],

the critical orbits are labeled by certain two-dimensional planes in the linear space of complex polynomials. This observation suggests to apply the Schubert calculus to this problem. In the present paper we realize this approach.

The Wronski determinant of two polynomials in one variable defines a map from the Grassmannian of two-dimensional planes of the linear space of complex polynomials to the space of monic polynomials called *the Wronski map*.

The function $\Phi(t)$ turns out to be the generating function of the Wronski map: the critical orbits label planes in the preimage under this map of the polynomial

$$W(x) = (x - z_1)^{\lambda_1} \dots (x - z_n)^{\lambda_n}.$$

In fact, this is a reformulation of a classical result going back to Heine and Stieltjes, Ch. 6.8 of [Sz].

To calculate the cardinality of the preimage of the Wronski map is a problem of enumerative algebraic geometry, and an upper bound can be easily obtained in terms of the intersection number of special Schubert classes. A well-known relation between representation theory and the Schubert calculus ([F]) implies that the obtained upper bound coincides with the dimension of $\text{Sing}_k(L)$.

In Sec. 2 we collect known facts related to the Gaudin model. In Sec. 3 we show that the function defining the Bethe equations is the generating function of the Wronski map, and in Sec. 4 we obtain an upper bound for the number of critical orbits of the generating function in terms of the intersection number of special Schubert classes.

Another conjecture related to the Gaudin model says that for generic z the Gaudin hamiltonians have a simple spectrum. In [ReV] it was proved that Bethe vectors are differ by their eigenvalues for generic $\lambda_1, \dots, \lambda_n$ and real z of the form $z_j = s^j$, where $s \gg 1$. If it is known that the Bethe vectors form a basis, then the simplicity of the spectrum follows.

In Sec. 5 we deduce the simplicity of the spectrum of the Gaudin hamiltonians for generic z and integral dominant sl_2 weights from the relation to Fuchsian differential equations described in [SV].

The arguments presented here work and give the similar results for the sl_p Gaudin model associated with the tensor product of symmetric powers of the standard sl_p -representation, see Sec. 5 of [S1]. The link between the Bethe vectors and the Wronski maps seems to be useful for study rational maps; see [S2] where the case of rational functions is treated.

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2. GAUDIN'S MODEL

2.1. The Gaudin hamiltonians. Let m_1, \dots, m_n be nonnegative integers, $M = (m_1, \dots, m_n)$. Denote L_{m_j} the irreducible sl_2 -module with highest weight m_j . The space of states of the Gaudin model is the tensor product

$$(1) \quad L^{\otimes M} = L_{m_1} \otimes \cdots \otimes L_{m_n}.$$

Associate with any L_{m_j} a complex number z_j^0 , and assume z_1^0, \dots, z_n^0 to be pairwise distinct numbers, $z^0 = (z_1^0, \dots, z_n^0)$. Let e, f, h be the standard generators of sl_2 ,

$$[e, f] = h, \quad [h, e] = 2e, \quad [h, f] = -2f$$

and

$$\Omega = e \otimes f + f \otimes e + \frac{1}{2}h \otimes h \in sl_2 \otimes sl_2$$

the Casimir element. For $1 \leq i < j \leq n$, denote $\Omega_{ij} : L^{\otimes M} \rightarrow L^{\otimes M}$ the operator which acts as Ω on i -th and j -th factors of $L^{\otimes M}$ and as the identity on all others. The hamiltonians of the Gaudin model are defined as follows,

$$(2) \quad \mathcal{H}_i(z^0) = \sum_{j \neq i} \frac{\Omega_{ij}}{z_i^0 - z_j^0}, \quad i = 1, \dots, n.$$

2.2. Subspaces of singular vectors. Write $|M| = m_1 + \cdots + m_n$. For a nonnegative integer k such that $|M| - 2k \geq 0$, define Sing_k , the subspace of singular vectors of weight $|M| - 2k$ in $L^{\otimes M}$,

$$(3) \quad \text{Sing}_k = \text{Sing}_k(L^{\otimes M}) = \{ w \in L^{\otimes M} \mid ew = 0, \quad hw = (|M| - 2k)w \}.$$

Theorem 1. ([SV], Theorem 5) *We have*

$$\dim \text{Sing}_k(L^{\otimes M}) = \sum_{q=0}^n (-1)^q \sum_{1 \leq i_1 < \cdots < i_q \leq n} \binom{k + n - 2 - m_{i_1} - \cdots - m_{i_q} - q}{n - 2},$$

where we assume $\binom{a}{b} = 0$ for $a < b$. \triangleleft

The subspace Sing_k is an invariant subspace of the Gaudin hamiltonians for any $0 \leq k \leq |M|/2$, and the singular vectors generate the whole of $L^{\otimes M}$. Therefore it is enough to diagonalize Gaudin hamiltonians in a given Sing_k .

2.3. Bethe equations associated to Sing_k and z^0 . The Bethe equations for the Gaudin model associated to Sing_k and z^0 have the form

$$(4) \quad \sum_{l=1}^n \frac{m_l}{t_i - z_l^0} = \sum_{j \neq i} \frac{2}{t_i - t_j}, \quad i = 1, \dots, k.$$

Any solution $t^0 = (t_1^0, \dots, t_k^0)$ to this system define an eigenvector $v(t^0) \in \text{Sing}_k$ of the Gaudin hamiltonians, $\mathcal{H}_j(z^0)v(t^0) = \mu_j v(t^0)$, with eigenvalues

$$(5) \quad \mu_j = \mu_j(t^0) = \sum_{l \neq j} \frac{m_l m_j}{2(z_j^0 - z_l^0)} - \sum_{i=1}^k \frac{m_j}{z_j^0 - t_i^0}, \quad j = 1, \dots, n.$$

2.4. The master function of the Gaudin model. Consider the following function in variables $t = (t_1, \dots, t_k)$ and $z = (z_1, \dots, z_n)$,

$$(6) \quad \Psi(t, z) = \prod_{1 \leq i < j \leq n} (z_i - z_j)^{m_i m_j / 2} \prod_{i=1}^k \prod_{l=1}^n (t_i - z_l)^{-m_l} \prod_{1 \leq i < j \leq k} (t_i - t_j)^2,$$

defined on

$$(7) \quad \mathcal{C} = \mathcal{C}(t; z) = \{ t \in \mathbb{C}^k, z \in \mathbb{C}^n \mid t_i \neq z_j, t_i \neq t_l, z_j \neq z_q, 1 \leq i \neq l \leq k, 1 \leq j \neq q \leq n \}.$$

Write

$$S(t, z) = \ln \Psi(t, z) = \sum_{1 \leq i < j \leq n} \frac{m_i m_j}{2} \ln(z_i - z_j) - \sum_{i=1}^k \sum_{l=1}^n m_l \ln(t_i - z_l) + \sum_{1 \leq i < j \leq k} 2 \ln(t_i - t_j).$$

The both functions $S(t, z)$ and $\Psi(t, z)$ have clearly the same critical set in $\mathcal{C}(t; z)$. Denote

$$Z = \{ z \in \mathbb{C}^n \mid z_j \neq z_q, 1 \leq j \neq q \leq n \}.$$

Let $\pi : \mathcal{C} \rightarrow Z$, $\pi(t, z) = z$, be the natural projection. For fixed $z^0 \in Z$, the equations (4) form a critical point system of the function $S(t, z^0)$ considered as a function in t on $\pi^{-1}(z^0)$,

$$\frac{\partial S}{\partial t_i}(t, z^0) = 0, \quad i = 1, \dots, k,$$

and the equalities (5) can be re-written in the form

$$\mu_j = \frac{\partial S}{\partial z_j}(t^0, z^0), \quad j = 1, \dots, n,$$

where $t^0 = t^0(z^0)$ is a solution to the Bethe equations. In terms of the function $\Psi(t, z)$, the Bethe equations (4) are

$$\frac{1}{\Psi(t, z^0)} \cdot \frac{\partial \Psi}{\partial t_i}(t, z^0) = 0, \quad i = 1, \dots, k,$$

and

$$\mu_j = \frac{1}{\Psi(t^0, z^0)} \cdot \frac{\partial \Psi}{\partial z_j}(t^0, z^0), \quad j = 1, \dots, n.$$

2.5. The Shapovalov form. Let m is a nonnegative integer. For the sl_2 -module L_m with highest weight m , fix the highest weight singular vector

$$v_m \in L_m, \quad hv_m = mv_m, \quad ev_m = 0.$$

Denote B_m the unique bilinear symmetric form on L_m such that

$$B_m(v_m, v_m) = 1, \quad B_m(hx, y) = B_m(x, hy), \quad B_m(ex, y) = B_m(x, fy)$$

for all $x, y \in L_m$. The vectors $v_m, fv_m, \dots, f^m v_m$ are orthogonal with respect to B_m and form a basis of L_m .

The bilinear symmetric form on $L^{\otimes M}$ given by

$$(8) \quad B = B_{m_1} \otimes \dots \otimes B_{m_n}$$

is called *the Shapovalov form*.

Let j_1, \dots, j_n be integers such that $0 \leq j_i \leq m_i$ for any $1 \leq i \leq n$. Write $J = (j_1, \dots, j_n)$ and $|J| = j_1 + \dots + j_n$. Denote

$$(9) \quad f^J v_M = f^{j_1} v_{m_1} \otimes \dots \otimes f^{j_n} v_{m_n}.$$

The vectors $\{f^J v_M\}$ are orthogonal with respect to the Shapovalov form B and provide a basis of the space $L^{\otimes M}$. We have

$$h(f^J v_M) = (|M| - 2|J|)f^J v_M, \quad e(f^J v_M) = 0,$$

i.e. the vector $f^J v_M$ is a *singular vector of weight* $|M| - 2|J|$. The space Sing_k is generated by the vectors $f^J v_M$ with $|J| = k$.

2.6. Bethe vectors. For $J = (j_1, \dots, j_n)$ with integer coordinates such that $0 \leq j_i \leq m_i$ and $|J| = k$ and for (t, z) in \mathcal{C} given by (7) set

$$A_J(t, z) = \frac{1}{j_1! \dots j_n!} \text{Sym}_t \left[\prod_{l=1}^n \prod_{i=1}^{j_l} \frac{1}{t_{j_1 + \dots + j_{l-1} + i} - z_l} \right],$$

where

$$\text{Sym}_t F(t) = \sum_{\sigma \in S^k} F(t_{\sigma(1)}, \dots, t_{\sigma(k)})$$

is the sum over all permutations of t_1, \dots, t_k .

Theorem 2. ([ReV]) (i) If $t^{(i)}$ is a nondegenerate critical point of the function $S(t, z^0)$, then the vector

$$(10) \quad v(t^{(i)}, z^0) = \sum_{J: |J|=k} A_J(t^{(i)}, z^0) f^J v_M$$

is an eigenvector of the operators $\mathcal{H}_1(z^0), \dots, \mathcal{H}_n(z^0)$.

(ii) For generic z^0 , the eigenvectors $v(t^{(i)}, z^0)$ corresponding to all critical point of the function $S(t, z^0)$ generate Sing_k . \triangleleft

The words “generic z^0 ” mean that z^0 does not belong to a suitable proper algebraic set of \mathbb{C}^n .

The set of critical points of the function $S(t, z^0)$ is invariant with respect to the permutations of t_1, \dots, t_k , and critical points belonging to the same orbit clearly define the same vector. Theorem 2 gives a lower bound for the number of critical orbits of the function $S(t, z^0)$ by the dimension of Sing_k . In [SV] the upper bound by the same number was obtained.

Theorem 3. [SV] *For fixed generic z^0 , all critical points of the function $S(t, z^0)$ are nondegenerate, and the number of orbits of critical points is at most the dimension of Sing_k .* \triangleleft

Corollary 1. [SV] *For generic z^0 , the Bethe vectors of the sl_2 Gaudin model form a basis in the space of singular vectors of a given weight.* \triangleleft

The statement that all critical points of the function $S(t, z^0)$ are nondegenerate is easy, see Theorem 6 in [SV]. The difficult part of [SV] was to estimate from above the number of critical orbits (see Theorems 9–11 in [SV]). As we pointed out in Sec. 1.4 of [SV], the orbits of critical points of the function $S(t, z^0)$ are labeled by certain two-dimensional planes in the linear space of complex polynomials. This observation suggests to apply the Schubert calculus in order to prove the following

Proposition. *The number of orbits of critical points of the function $S(t, z^0)$ is at most the dimension of Sing_k .*

As we will see below, within the framework of the Schubert calculus, the Proposition is a direct and immediate corollary of easy Theorem 7 of Sec. 4.2.

3. THE GENERATING FUNCTION OF THE WRONSKI MAP

3.1. The Wronski map. Let Poly_d be the vector space of complex polynomials of degree at most d in one variable. Denote $G_2(\text{Poly}_d)$ the Grassmannian of two-dimensional planes in Poly_d . The complex dimension of $G_2(\text{Poly}_d)$ is $2d - 2$.

For any $V \in G_2(\text{Poly}_d)$ define the *degree* of V as the maximal degree of its polynomials and the *order* of V as the minimal degree of its non-zero polynomials. Let $V \in G_2(\text{Poly}_d)$ be a plane of order a and of degree b . Clearly $0 \leq a < b \leq d$. Choose in V two monic polynomials, $F(x)$ and $G(x)$, of degrees a and b respectively. They form a basis of V . The *Wronskian* of V is defined as the monic polynomial

$$W_V(x) = \frac{F'(x)G(x) - F(x)G'(x)}{a - b}.$$

The following lemma is evident.

Lemma 1. (i) *The degree of $W_V(x)$ is $a + b - 1 \leq 2d - 2$.*

(ii) *The polynomial $W_V(x)$ does not depend on the choice of a monic basis.*

(iii) *All polynomials of degree a in V are proportional.* \triangleleft

Thus the mapping sending $V \in G_2(\text{Poly}_d)$ to $W_V(x)$ is a well-defined map from the Grassmannian $G_2(\text{Poly}_d)$ to \mathbb{CP}^{2d-2} . We call it *the Wronski map*. This is a mapping between smooth complex algebraic varieties of the same dimension, and hence the preimage of any polynomial consists of a finite number of planes. On Wronski maps see [EGa].

3.2. Planes with a given Wronskian.

Lemma 2. *Any element of $G_2(\text{Poly}_d)$ with a given Wronskian is uniquely determined by any of its polynomial.*

Proof: Let $W(x)$ be the Wronskian of a plane $V \in G_2(\text{Poly}_d)$ and $f(x) \in V$. Take any polynomial $g(x) \in V$ linearly independent with $f(x)$. The plane V is the solution space of the following second order linear differential equation with respect to unknown function $u(x)$,

$$\begin{vmatrix} u(x) & f(x) & g(x) \\ u'(x) & f'(x) & g'(x) \\ u''(x) & f''(x) & g''(x) \end{vmatrix} = 0.$$

The Wronskian of the polynomials $f(x)$ and $g(x)$ is proportional to $W(x)$, therefore this equation can be re-written in the form

$$W(x)u''(x) - W'(x)u'(x) + h(x)u(x) = 0,$$

where

$$h(x) = \frac{-W(x)f''(x) + W'(x)f'(x)}{f(x)},$$

as $f(x)$ is clearly a solution to this equation. \triangleleft

We call a plane $V \in G_2(\text{Poly}_d)$ *generic* if for any $x_0 \in \mathbb{C}$ there is a polynomial $P(x) \in V$ such that $P(x_0) \neq 0$. In a generic plane, the polynomials of any basis do not have common roots, and almost all polynomials of the bigger degree do not have multiple roots.

The following lemma is evident.

Lemma 3. *Let $V \in G_2(\text{Poly}_d)$ be a generic plane.*

(i) *If $P(x) = (x - x_1) \dots (x - x_l) \in V$ is a polynomial without multiple roots, then $W_V(x_i) \neq 0$ for all $1 \leq i \leq l$.*

(ii) *If x_0 is a root of multiplicity $\mu > 1$ of a polynomial $Q(x) \in V$, then x_0 is a root of $W_V(x)$ of multiplicity $\mu - 1$.* \triangleleft

A generic plane V is *nondegenerate* if the polynomials of the smaller degree in V do not have multiple roots.

Lemma 4. *Let $V \in G_2(\text{Poly}_d)$ be a nondegenerate plane. If the Wronskian $W_V(x)$ has the form*

$$W_V(x) = x^m \tilde{W}(x), \quad \tilde{W}(0) \neq 0,$$

then there exists a polynomial $F_0(x) \in V$ of the form

$$F_0(x) = x^{m+1} \tilde{F}(x), \quad \tilde{F}(0) \neq 0.$$

Proof: Let $G(x) \in V$ be a polynomial of the smaller degree. We have $G(0) \neq 0$, due to Lemma 3. Let $F(x) \in V$ be a polynomial of the bigger degree. The polynomial

$$F_0(x) = F(x) - \frac{F(0)}{G(0)} G(x) \in V$$

satisfies $F_0(0) = 0$ and therefore has the form

$$F_0(x) = x^l \tilde{F}(x), \quad \tilde{F}(0) \neq 0,$$

for some integer $l \geq 1$. The polynomials G and F_0 form a basis of V , therefore the polynomial $F'_0(x)G(x) - F_0(x)G'(x)$ is proportional to $W_V(x)$. The smallest degree term in this polynomial is $l \cdot a_l \cdot G(0)x^{l-1}$, where a_l is the coefficient of x^l in $F_0(x)$. Therefore $l = m + 1$. \triangleleft

3.3. Nondegenerate planes in Poly_d with a given Wronskian. Recall that *the resultant* $\text{Res}(P, Q)$ of polynomials $P(x)$ and $Q(x)$ is an irreducible integral polynomial in the coefficients of $P(x)$ and $Q(x)$ which vanishes whenever $P(x)$ and $Q(x)$ have a common root, and *the discriminant* $\Delta(P)$ of $P(x)$ is an irreducible integer polynomial in the coefficients of $P(x)$ which vanishes whenever $P(x)$ has a multiple root.

Our aim is to describe the nondegenerate planes of a given order in the preimage of the polynomial

$$(11) \quad W(x) = (x - z_1)^{m_1} \dots (x - z_n)^{m_n}.$$

under the Wronski map.

If plane V of order k and of degree d has the Wronskian $W(x)$, then $d = |M| + 1 - k > k$. Let $F(x)$ be an unknown polynomial of degree $1 \leq k \leq |M|/2$. Consider the following function, which appeared in unpublished notes of V. Zakalyukin related to the Wronski map,

$$\Phi = \Phi(F; W) = \frac{\Delta(F)}{\text{Res}(W, F)}.$$

If the polynomial $F(x)$ belongs to a plane in $\text{Poly}_{|M|+1-k}$ with the Wronskian $W(x)$, then $W(x) = F'(x)Q(x) - F(x)Q'(x)$ for some polynomial $Q(x)$. Differentiating gives $W'(x) = F''(x)Q(x) - F(x)Q''(x)$, and we have

$$\frac{W'}{W} = \frac{F''Q - FQ''}{F'Q - FQ'}.$$

If the plane spanned by $F(x)$ and $G(x)$ is non-degenerate, then polynomials F and Q do not have common roots, polynomial F does not have multiple roots, and polynomials

W and F do not have common roots, by Lemmas 3 and 4. Therefore at each root t_i of F we get

$$(12) \quad \frac{W'(t_i)}{W(t_i)} = \frac{F''(t_i)}{F'(t_i)}, \quad i = 1, \dots, k.$$

3.4. Theorem of Heine–Stieltjes. In order to re-write the function Φ as a function in unknown roots of $F(x)$, recall that if $F(x) = (x - t_1) \dots (x - t_k)$ and if $W(x)$ is as in (11), then

$$\Delta(F) = \prod_{1 \leq i < j \leq k} (t_i - t_j)^2, \quad \text{Res}(W, F) = \prod_{i=1}^k \prod_{j=1}^n (t_i - z_j)^{m_j}.$$

We have

$$(13) \quad \Phi = \Phi(t; z, M) = \prod_{i=1}^k \prod_{l=1}^n (t_i - z_l)^{-m_l} \prod_{1 \leq i < j \leq k} (t_i - t_j)^2.$$

The critical points of this function were studied by Heine and Stieltjes in connection with second order linear differential equations having polynomial coefficients and a polynomial solution of a prescribed degree. The result of Heine and Stieltjes can be formulated as follows.

Theorem 4. (Heine–Stieltjes, cf. [Sz], Ch. 6.8) *Let t^0 be a critical point with non-zero critical value of the function $\Phi(t)$ given by (13). Then $F(x) = (x - t_1^0) \dots (x - t_k^0)$ is a polynomial of the smaller degree in a nondegenerate plane with the Wronskian $W(x)$ given by (11).*

Conversely, if $F(x) = (x - t_1^0) \dots (x - t_k^0)$ is a polynomial of the smaller degree in a non-degenerate plane V with the Wronskian $W_V(x) = W(x)$, then $t^0 = (t_1^0, \dots, t_k^0)$ is a critical point with non-zero critical value of the function $\Phi(t)$. \triangleleft

The function $\Phi(t)$ is symmetric with respect to permutations of t_1, \dots, t_k , critical points belonging to one orbit define the same polynomial $F(x)$ and hence, according to Lemma 2, the same plane.

3.5. Bethe vectors and nondegenerate planes. The function $\Phi(t)$ given by (13) and the function $\Psi(t, z)$ given by (6) differ in a factor depending only on z and M ,

$$\Psi(t, z) = \prod_{1 \leq i < j \leq n} (z_i - z_j)^{m_i m_j / 2} \cdot \Phi(t; z, M).$$

An easy calculation shows that (12) is exactly the system defining the critical points with non-zero critical values of the function Φ , considered as a function in t . The theorem of Heine–Stieltjes implies the following result.

Corollary 2. *There is a one-to-one correspondence between the critical orbits with non-zero critical value of the function (13) and the nondegenerate planes of order k and of degree $|M| + 1 - k$ having Wronskian (11).* \triangleleft

Corollary 3. *For fixed $z \in Z$, $M = (m_1, \dots, m_n)$ and k , there is a one-to-one correspondence between the Bethe vectors of the sl_2 Gaudin model associated to z and Sing_k given by (3) and nondegenerate planes of order k with the Wronskian (11). \triangleleft*

Corollary 4. *The Bethe equations associated to z and (3) coincide with the critical point system of the generating function associated to order k and the Wronskian (11). \triangleleft*

The function Φ is called *the generating function* of the Wronski map: for any given monic polynomial $W(x)$ and any given order $k \leq \deg W/2$, the critical orbits of the function Φ determine the non-degenerate planes of order k in the preimage of $W(x)$. We will show below that for generic z the critical orbits determine *all* planes of order k in the preimage, see Corollary 5 in Sec. 4.2.

4. THE PREIMAGE OF A GIVEN WRONSKIAN

The number of nondegenerate planes with a given Wronskian can be estimated from above by the intersection number of Schubert classes.

4.1. Schubert calculus ([GrH], [F]). Let $G_2(d+1) = G_2(\mathbb{C}^{d+1})$ be the Grassmannian variety of two-dimensional subspaces $V \subset \mathbb{C}^{d+1}$. A chosen basis e_1, \dots, e_{d+1} of \mathbb{C}^{d+1} defines the flag of linear subspaces

$$E_\bullet : E_1 \subset E_2 \subset \dots \subset E_d \subset E_{d+1} = \mathbb{C}^{d+1},$$

where $E_i = \text{Span}\{e_1, \dots, e_i\}$, $\dim E_i = i$. For any integers a_1 and a_2 such that $0 \leq a_2 \leq a_1 \leq d-1$, the *Schubert variety* $\Omega_{a_1, a_2}(E_\bullet) \subset G_2(d+1)$ is defined as follows,

$$\Omega_{a_1, a_2} = \Omega_{a_1, a_2}(E_\bullet) = \{V \in G_2(d+1) \mid \dim(V \cap E_{d-a_1}) \geq 1, \dim(V \cap E_{d+1-a_2}) \geq 2\}.$$

The variety $\Omega_{a_1, a_2} = \Omega_{a_1, a_2}(E_\bullet)$ is an irreducible closed subvariety of $G_2(d+1)$ of the complex codimension $a_1 + a_2$.

The homology classes $[\Omega_{a_1, a_2}]$ of Schubert varieties Ω_{a_1, a_2} are independent of the choice of flag, and form a basis for the integral homology of $G_2(d+1)$. Denote σ_{a_1, a_2} the cohomology class in $H^{2(a_1+a_2)}(G_2(d+1))$ whose cap product with the fundamental class of $G_2(d+1)$ is the homology class $[\Omega_{a_1, a_2}]$. The classes σ_{a_1, a_2} are called *Schubert classes*. They give a basis over \mathbb{Z} for the cohomology ring of the Grassmannian. The product or *intersection* of any two Schubert classes σ_{a_1, a_2} and σ_{b_1, b_2} has the form

$$\sigma_{a_1, a_2} \cdot \sigma_{b_1, b_2} = \sum_{c_1+c_2=a_1+a_2+b_1+b_2} C(a_1, a_2; b_1, b_2; c_1, c_2) \sigma_{c_1, c_2},$$

where $C(a_1, a_2; b_1, b_2; c_1, c_2)$ are nonnegative integers called *the Littlewood–Richardson coefficients*.

If the sum of the codimensions of classes equals $\dim G_2(d+1) = 2d-2$, then their intersection is an integer (identifying the generator of the top cohomology group $\sigma_{d-1, d-1} \in H^{4d-4}(G_2(d+1))$ with $1 \in \mathbb{Z}$) called *the intersection number*.

When $(a_1, a_2) = (q, 0)$, $0 \leq q \leq d-1$, the Schubert varieties $\Omega_{q,0}$ are called *special* and the corresponding cohomology classes $\sigma_q = \sigma_{q,0}$ are called *special Schubert classes*.

The Littlewood–Richardson coefficients appear as well in the decomposition of the tensor product of two irreducible finite-dimensional sl_2 -modules into the direct sum of irreducible sl_2 -modules. This leads to the following claim connecting Schubert calculus and representation theory.

Denote L_q the irreducible sl_2 -module with highest weight q .

Theorem 5. [F] *Let q_1, \dots, q_{n+1} be integers such that $0 \leq q_i \leq d-1$ for all $1 \leq i \leq n+1$ and $q_1 + \dots + q_{n+1} = 2d-2$. The intersection number of the special Schubert classes, $\sigma_{q_1} \cdot \dots \cdot \sigma_{q_{n+1}}$, coincides with the multiplicity of the trivial sl_2 -module L_0 in the tensor product $L_{q_1} \otimes \dots \otimes L_{q_{n+1}}$.* \triangleleft

Theorems 1 and 5 imply the following explicit formula.

Theorem 6. *Let q_1, \dots, q_{n+1} be integers such that $0 \leq q_i \leq d-1$ for all $1 \leq i \leq n+1$ and $q_1 + \dots + q_{n+1} = 2d-2$. Then*

$$\sum_{l=1}^n (-1)^{n-l} \sum_{1 \leq i_1 < \dots < i_l \leq n} \binom{q_{i_1} + \dots + q_{i_l} + l - d - 1}{n-2}$$

is the intersection number $\sigma_{q_1} \cdot \dots \cdot \sigma_{q_{n+1}}$. \triangleleft

We did not find this formula in the literature on the Schubert calculus.

4.2. Planes with a given Wronskian and Schubert classes. Applying the Schubert calculus to the Wronski map, we arrive at the following result.

Theorem 7. *Let m_1, \dots, m_n be positive integers, $|M| = m_1 + \dots + m_n$. For generic $z \in Z$ and for any integer k such that $1 \leq k < |M|+1-k$, the preimage of the polynomial (11) under the Wronski map consists of at most*

$$\sigma_{m_1} \cdot \dots \cdot \sigma_{m_n} \cdot \sigma_{|M|-2k}$$

nondegenerate planes of order k and of degree $< |M|+1-k$.

Proof: Any plane of order k with the Wronskian of degree $|M|$ lies in $G_2(\text{Poly}_{|M|+1-k})$, as Lemma 1 shows. Therefore it is enough to consider the Wronski map on $G_2(\text{Poly}_{|M|+1-k})$.

For any z_j , define the flag \mathcal{F}_{z_j} in $\text{Poly}_{|M|+1-k}$,

$$\mathcal{F}_0(z_j) \subset \mathcal{F}_1(z_j) \subset \dots \subset \mathcal{F}_{|M|+1-k}(z_j) = \text{Poly}_{|M|+1-k},$$

where $\mathcal{F}_i(z_j)$ consists of the polynomials $P(x) \in \text{Poly}_{|M|+1-k}$ of the form

$$P(x) = a_i(x - z_j)^{|M|+1-k-i} + \dots + a_0(x - z_j)^{|M|+1-k}.$$

We have $\dim \mathcal{F}_i(z_j) = i+1$. Lemma 4 implies that the nondegenerate planes with a Wronskian having at z_j a root of multiplicity m_j lie in the special Schubert variety

$$\Omega_{m_j,0}(\mathcal{F}_{z_j}) \subset G_2(\text{Poly}_{|M|+1-k}).$$

The maximal possible degree of the Wronskian $W_V(x)$ for $V \in \text{Poly}_{|M|+1-k}$ is clearly $2|M| - 2k$. Denote $m_\infty = |M| - 2k$, the difference between $2|M| - 2k$ and $|M|$. If m_∞ is positive, it is *the multiplicity of $W(x)$ at infinity*.

The nondegenerate planes with a Wronskian having given multiplicity m_∞ at infinity lie in the special Schubert variety $\Omega_{m_\infty,0}(\mathcal{F}_\infty)$, where \mathcal{F}_∞ is the flag

$$\text{Poly}_0 \subset \text{Poly}_1 \subset \cdots \subset \text{Poly}_{|M|+1-k}.$$

We conclude that the nondegenerate planes of order k which have the Wronskian (11) lie in the intersection of special Schubert varieties

$$\Omega_{m_1,0}(\mathcal{F}_{z_1}) \cap \Omega_{m_2,0}(\mathcal{F}_{z_2}) \cap \cdots \cap \Omega_{m_n,0}(\mathcal{F}_{z_n}) \cap \Omega_{m_\infty,0}(\mathcal{F}_\infty).$$

The dimension of $G_2(\text{Poly}_{|M|+1-k})$ is exactly $m_1 + \cdots + m_n + m_\infty$, therefore this intersection consists of a finite number of planes, and the intersection number of the special Schubert classes

$$\sigma_{m_1} \cdot \cdots \cdot \sigma_{m_n} \cdot \sigma_{|M|-2k}$$

provides an upper bound. \triangleleft

Theorems 5 and 7, together with Corollary 2, imply the Proposition of Sec. 2.6.

Corollary 5. *For generic $z \in Z$, all planes in the preimage under the Wronski map of the polynomial $W(x)$ given by (11) are nondegenerate.* \triangleleft

5. THE SIMPLICITY OF THE SPECTRUM OF THE GAUDIN HAMILTONIANS

5.1. Fuchsian differential equations with only polynomial solutions and the Wronski map. Consider a second order Fuchsian differential equation with regular singular points at z_1, \dots, z_n , $n \geq 2$, and at infinity. If the exponents at z_j are 0 and $m_j + 1$, $1 \leq j \leq n$, then this equation has the form

$$(14) \quad \begin{aligned} F(x)u''(x) + G(x)u'(x) + H(x)u(x) &= 0, \\ F(x) &= \prod_{j=1}^n (x - z_j), \quad \frac{G(x)}{F(x)} = \sum_{j=1}^n \frac{-m_j}{x - z_j}, \end{aligned}$$

where $H(x)$ is a polynomial of degree not greater than $n - 2$. On Fuchsian equations see Ch. 6 of [R].

Theorem 8. *Any nondegenerate plane $V \in G_2(\text{Poly}_d)$ with the Wronskian (11) is the solution space of such an equation.*

Proof: Let $f(x)$ and $g(x)$ be non-zero monic polynomials in V such that $\deg f < \deg g$. As we have seen in course of the proof of Lemma 2, the plane V is the solution space of the equation

$$W(x)u''(x) - W'(x)u'(x) + h(x)u(x) = 0,$$

where

$$h(x) = \frac{-W(x)f''(x) + W'(x)f'(x)}{f(x)}$$

is a polynomial proportional to the Wronskian of $f'(x)$ and $g'(x)$. One can easily check that

$$\frac{W'(x)}{W(x)} = \sum_{j=1}^n \frac{m_j}{x - z_j}.$$

Moreover, if z_j is a root of $W(x)$ of multiplicity $m_j > 1$, then all coefficients of the equation have $(x - z_j)^{m_j-1}$ as a common factor, and the equation can be reduced to the required form (14). \triangleleft

In [Fr], a correspondence between eigenvalues of the Gaudin hamiltonians and the sl_2 -opers which determine a trivial monodromy representation

$$\pi_1(P^1 \setminus \{z_1, \dots, z_n, \infty\}) \rightarrow PGL_2$$

was established. Notice that any nondegenerate plane with a given Wronskian defines such an oper, and any oper with trivial monodromy defines a plane in $G_2(\text{Poly}_d)$ for some d .

5.2. Bethe vectors are differ by their eigenvalues. Let $t^{(1)}$ and $t^{(2)}$ be two solutions to the Bethe equations (4) associated to fixed $z^0 \in Z$ and Sing_k . Denote $v(t^{(i)}, z^0)$ the corresponding Bethe vectors given by (10) and $\mu^{(i)} = (\mu_1(t^{(i)}), \dots, \mu_n(t^{(i)}))$ their eigenvalues given by (5), $i = 1, 2$.

Theorem 9. *If $\mu^{(1)} = \mu^{(2)}$, then $v(t^{(1)}, z^0) = v(t^{(2)}, z^0)$.*

Proof: Let $f_i(x) = (x - t_1^{(i)}) \dots (x - t_k^{(i)})$ be the corresponding polynomials, $i = 1, 2$. Any of these polynomials defines a differential equation of the form (14). A classical fact of the theory of Fuchsian equations is that if an equation of the form (14) with positive integer m_1, \dots, m_n has a polynomial solution without multiple roots, then all solutions to this equation are polynomials, see Ch. 6 of [R] or Sec. 3.1 of [SV]. We have

$$H_i(x) = -\frac{F(x)f_i''(x) + G(x)f_i'(x)}{f_i(x)}, \quad i = 1, 2.$$

Polynomials $H_1(x)$ and $H_2(x)$ have degree at most $n - 2$. We will show that these polynomials in fact coincide. Indeed, the substitution of z_j into H_i gives

$$H_i(z_j) = m_j \cdot \frac{f_i'(z_j)}{f_i(z_j)} \prod_{l \neq j}^n (z_j - z_l).$$

An easy calculation shows that

$$\frac{f_i'(z_j)}{f_i(z_j)} = \sum_{l=1}^k \frac{1}{z_j - t_l^{(i)}},$$

and the condition $\mu^{(1)} = \mu^{(2)}$ together with (5) imply

$$\frac{f_1'(z_j)}{f_1(z_j)} = \frac{f_2'(z_j)}{f_2(z_j)}, \quad j = 1, \dots, n.$$

We conclude that polynomials $H_i(x)$ coincide at n points, therefore $H_1(x) = H_2(x)$. Thus polynomials $f_1(x)$ and $f_2(x)$ are monic polynomials of the minimal degree in the same solution plane. Hence $f_1(x) = f_2(x)$, the solutions $t^{(1)}$ and $t^{(2)}$ of the Bethe equations lie in the same orbit, and $v(t^{(1)}, z^0) = v(t^{(2)}, z^0)$. \triangleleft

Corollary 6. *For generic $z^0 \in Z$, the sl_2 Gaudin hamiltonians (2) have a simple spectrum.* \triangleleft

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